

# Geophysical Research Letters<sup>®</sup>










## RESEARCH LETTER

10.1029/2023GL106112

## Revealing the Key Drivers Conducive to the “Once-In-A-Century” 2021 Peninsular Malaysia Flood

### Key Points:

- A stretched moisture channel from Typhoon Rai and a strong tropical depression are key synoptic drivers for the flooding event
- Return period and joint probability of key drivers indicate that the 2021 Peninsular Malaysia flood was more severe than “once-in-a-century”
- There is an increasing trend in such anomalous moisture channel, suggesting a rising risk of severe flooding in Southeast Asia

Luojie Dong<sup>1</sup> , Jingyu Wang<sup>2</sup> , Xiefei Zhi<sup>3,4</sup> , Edward Park<sup>2,5</sup> , Xianfeng Wang<sup>5,6</sup> , Steve Hung-Lam Yim<sup>5,6,7</sup> , Hugh Zhang<sup>8</sup>, Joshua Lee<sup>8</sup> , and Dung Duc Tran<sup>2,9</sup> 

<sup>1</sup>School of Computer Science and Engineering, Nanyang Technological University, Singapore, Singapore, <sup>2</sup>National Institute of Education, Nanyang Technological University, Singapore, Singapore, <sup>3</sup>Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, China, <sup>4</sup>WeatherOnline Institute of Meteorological Applications, Wuxi, China, <sup>5</sup>Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore, <sup>6</sup>Asian School of the Environment, Nanyang Technological University, Singapore, Singapore, <sup>7</sup>Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore, Singapore, <sup>8</sup>Centre for Climate Research Singapore, Singapore, Singapore, <sup>9</sup>Center of Water Management and Climate Change, Vietnam National University, Ho Chi Minh City, Vietnam

### Supporting Information:

Supporting Information may be found in the online version of this article.

### Correspondence to:

J. Wang and X. Zhi,  
jingyu.wang@nie.edu.sg;  
zhi@nuist.edu.cn

### Citation:

Dong, L., Wang, J., Zhi, X., Park, E., Wang, X., Yim, S. H. -L., et al. (2023). Revealing the key drivers conducive to the “once-in-a-century” 2021 Peninsular Malaysia flood. *Geophysical Research Letters*, 50, e2023GL106112. <https://doi.org/10.1029/2023GL106112>

Received 26 AUG 2023

Accepted 10 NOV 2023

### Author Contributions:

**Conceptualization:** Jingyu Wang, Xiefei Zhi, Hugh Zhang, Joshua Lee, Dung Duc Tran

**Data curation:** Jingyu Wang

**Formal analysis:** Luojie Dong, Jingyu Wang, Xiefei Zhi

**Funding acquisition:** Jingyu Wang

**Investigation:** Luojie Dong, Jingyu Wang, Xiefei Zhi, Xianfeng Wang

**Methodology:** Jingyu Wang, Edward Park, Xianfeng Wang, Hugh Zhang

**Project Administration:** Jingyu Wang, Xiefei Zhi, Edward Park, Steve Hung-Lam Yim, Joshua Lee

**Supervision:** Jingyu Wang, Xiefei Zhi, Edward Park, Steve Hung-Lam Yim, Joshua Lee

© 2023. The Authors.

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

**Abstract** In December 2021, Super Typhoon Rai caused significant devastation to the South Philippines and East Malaysia. In the meantime, an unprecedented flood event occurred in Peninsular Malaysia at 2,000 km west of the typhoon's path, causing comparable socioeconomic impacts as Rai. Record-breaking 3-day precipitation was received by Peninsular Malaysia during 16–18 December. Based on the storm tracking results, this study identified two mesoscale convective systems (MCSs) that were directly responsible for the flooding. The two MCSs were directly initiated by a tropical depression and sustained by an elongated easterly water vapor corridor originating from the Super Typhoon Rai. The return period and joint frequency analysis of key drivers indicate that the 3-day downpour was more severe than a “once-in-a-century” event. Historical records suggest such anomalous moisture channel has become more frequent in Southeast Asia, which alarms heightened attention in forecasting winter flood.

**Plain Language Summary** On 16–18 December, Peninsular Malaysia received a record-shattering 3-day precipitation, resulting in catastrophic socioeconomic impacts. Due to the temporal coincidence with Super Typhoon Rai but far away in space, there were speculations that there might be a teleconnection between the two events. Our results reveal that their relationship could be more straightforward. Based on the analyses of storm tracking database and synoptic data records, we found that two consecutive mesoscale convective systems were responsible for the heavy precipitation, which were produced by a tropical depression that hovered over the peninsula. Meanwhile, Super Typhoon Rai provided a long-range water vapor transport, akin to adding fuel (i.e., moisture) to the engine (i.e., the tropical depression), and therefore, the precipitation over the peninsula was significantly enhanced. Such long-range moisture transport has become more frequent during the boreal winter season, posing an increasing risk of flooding in Southeast Asia.

## 1. Introduction

Super Typhoon Rai swept over the South Philippines and East Malaysia in the middle of December 2021, causing nearly 400 deaths, more than half a million people displaced, and economic loss at the billion-dollar (USD) level. This catastrophe has attracted worldwide attention because of the unprecedented severity and widespread socioeconomic impacts. While the typhoon ravaged the east portion of Southeast Asia (SEA), a “once-in-a-century” flooding event struck Peninsular Malaysia. The major flooding period lasted from 16 to 18 December 2021, before precipitation relented on 19 December. Record-breaking single-day rainfall was measured by several stations during the 3 days. For example, Sentul station in Kuala Lumpur recorded 363 mm in 24 hr, which was far greater than the average rainfall in Kuala Lumpur in a month (200 mm; Hassan, 2021). The flood series directly caused at least 51 deaths with 2 missing according to government officials (BERNAMA, 2022), and the displaced victims count was estimated to be as much as 67,576 cumulatively (NDCC, 2021). In terms of economic loss, according to the Statistics Department of Malaysia, the country suffered losses of between USD\$1.2 billion and USD\$1.5 billion.

**Resources:** Jingyu Wang, Xianfeng Wang, Steve Hung-Lam Yim, Hugh Zhang  
**Software:** Luojie Dong, Jingyu Wang, Edward Park, Xianfeng Wang, Steve Hung-Lam Yim  
**Supervision:** Jingyu Wang, Xiefei Zhi, Xianfeng Wang, Steve Hung-Lam Yim, Hugh Zhang, Joshua Lee  
**Validation:** Luojie Dong, Jingyu Wang  
**Visualization:** Luojie Dong, Jingyu Wang, Xiefei Zhi, Xianfeng Wang, Hugh Zhang  
**Writing – original draft:** Luojie Dong, Jingyu Wang, Edward Park, Dung Duc Tran  
**Writing – review & editing:** Luojie Dong, Jingyu Wang, Edward Park, Dung Duc Tran

Both the pre-event predictions and the post-event evaluation greatly underestimated the scale of this enormous flood. The Meteorological Department of Malaysia (MetMalaysia) issued an orange weather warning on 16 December 2021, which initially only affected limited districts in Kelantan and Terengganu (Malay Mail, 2021). The inadequacy of the warning level partially contributed to the unexpected loss of lives across the country. After the catastrophe, multiple mainstream media sources later described it as a “once-in-a-century” event, yet precise quantification was still lacking.

This study goes beyond statistics-based estimation of the return period of the extreme rainfall that led to the flooding. By adopting a state-of-the-art storm tracking algorithm, the mesoscale convective systems (MCSs) responsible for the production of the anomalous rainfall are first detected and tracked. Then, through the examination of the simultaneous environmental conditions throughout the MCSs' lifecycle, the key synoptic drivers, specifically the long-distance moisture transport resembling an atmospheric river (AR) and the landfall of a tropical depression (TD), are determined as the main contributors to the target MCSs. Finally, another return period is estimated through the examination of the joint probability of key driver that comprised the sufficient condition for the flood-causing MCSs. Consistency has been reached between the proxy-based method and the statistical model that the 2021 Peninsular Malaysia flood was more severe than “once-in-a-century.”

In addition to quantifying the extreme rainfall return period to benefit long-term strategic planning, this study identifies the synoptic drivers that are conducive to the flooding and have significant implications for operational weather forecasting. This study also reveals that such persistent zonal water vapor corridor within tropics has increased in occurrence in Southeast Asia (SEA) based on the historical records. Therefore, it is critical to prioritize the vigilance and monitoring of such anomalous phenomena in the forecasting and risk assessment of winter flooding in SEA.

## 2. Data and Methods

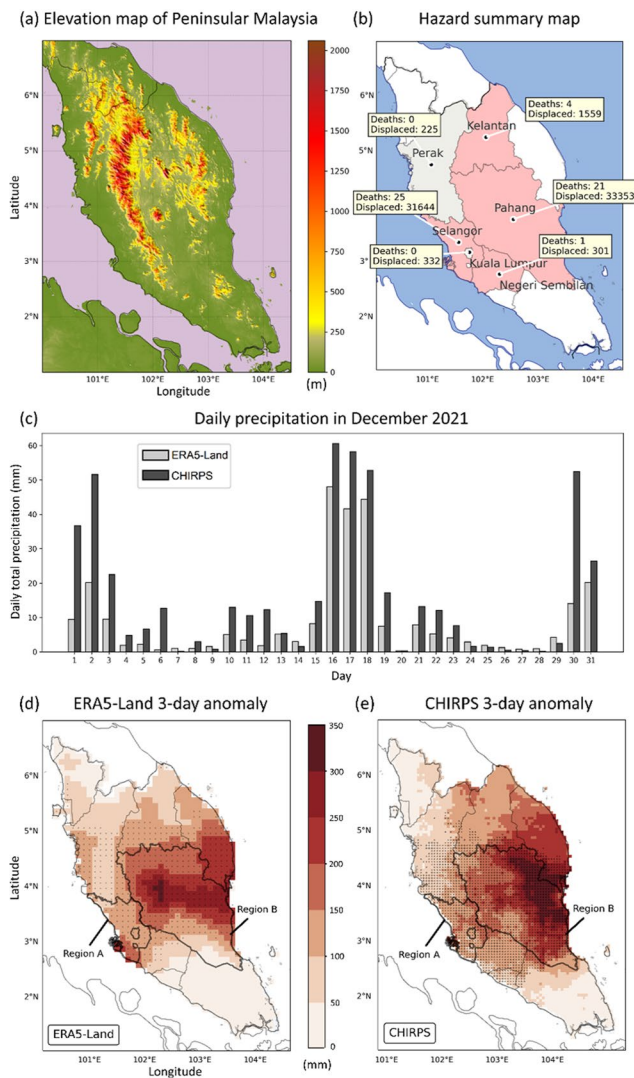
### 2.1. Case Description and Precipitation Data

The 2021–2022 Malaysian floods lasted more than 1 month from 16 December 2021 to 19 January 2022. During this flooding period, torrential rainfall swept both Peninsular Malaysia and East Malaysia. Unlike East Malaysia, where the majority of the precipitation was directly brought by outer rain band spawned by the Super Typhoon Rai, the extreme rainfall in Peninsular Malaysia mainly came from the westward propagating tropical depression. The north-south oriented Titiwangsa Mountains divides the peninsula into the western coastal area and eastern hilly plains (Figure 1a). When the easterly propagating TD encounters the mountain range, the orographic lifting invigorates the large-scale upward motion and subsequently enhances adiabatic cooling of the air column (Stull, 2017), which eventually intensifies rainfall over the eastern plains ranging from 3.5° to 6° N, where the mountain ridge reaches the highest elevation with the broadest zonal coverage. However, as the Titiwangsa blunts southeastward and merges into the eastern hilly plains, the orographic effect on precipitation distribution fades quickly, making the southwest foothill of the mountain chain also exposed to the severe rainfall. The hazard summary map (Figure 1b) corresponds well the terrain distribution, where the majority of casualty and displacements occurred in the state of Pahang (21 dead and 33,353 displaced) over the upwind side of Titiwangsa and the state of Selangor (25 dead and 31,633 displaced) over the southwest foothill. In comparison, the state of Perak on Lee side of the mountain was not severely affected with no casualty and few displaced persons.

Two data sets were obtained to analyze the precipitation pattern, namely the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 enhanced for the land component (ERA5-Land; hourly; 0.1 by 0.1°; Hersbach et al., 2020) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; daily; 0.05 by 0.05°; Funk et al., 2015).

To identify the time window of the most severe precipitation, as well as to cross-validate the two independent records, Figure 1c compares the daily total precipitation averaged over the entire Peninsular Malaysia between the two data sets in December 2021. A persistent overestimation is found in CHIRPS when compared to ERA5-Land (the ratio of CHIRPS estimation of monthly total precipitation in December 2021 over ERA5-Land is 1.8). However, a comparable temporal variation in daily total precipitation is observed, when the most prominent precipitation occurs at the beginning (1–3 December), middle (16–18), and end of the month (30–31).

By summing the December daily precipitation into 3-day totals (i.e., 1–3, 4–6, to 28–30), the 16–18 December 2021 event was compared to the historical precipitation records from ERA5-Land (1950–2021) and CHIRPS



**Figure 1.** (a) The elevation map of Peninsular Malaysia. (b) The summary map of casualty and displacements. (c) The domain average daily precipitation over the entire Peninsular Malaysia in December, obtained from ECMWF Reanalysis v5 enhanced for the land component (ERA5-Land) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). (d) Anomaly of 3-day precipitation by comparing the 16–18 December 2021 event to the 1950–2021 records using ERA5-Land data. Locations with significant positive anomaly (with statistical significance at the 95% confidence level based on a one-tailed  $z$  test) are marked with black dots. (e) Is same as (d), but the data set is changed to CHIRPS in 1981–2021.

(1981–2021) respectively. Figure 1d examine the spatial distribution of the precipitation anomalies observed by ERA5-Land. By checking the spatial pattern of the significant positive precipitation anomalies (black dots), most of those are distributed within the latitudinal band 3°–5°N, which correspond well to the high terrain of Titiwangsa (Figure 1a). By checking the absolute differences, the strongest wet anomalies are found on the upwind side of the mountain over the eastern plains. These findings echo the orographic invigoration of precipitation. A similar spatial pattern is also observed by CHIRPS (Figure 1e), however a stronger absolute difference is found in the latter data set and the core of the most intense positive anomalies is further shifted eastward to the coast. Despite of the mismatch in the location of the strongest anomalous precipitation core, the overall spatial consistency is reached between the two data sets, and two regions with the most severe precipitation anomaly (Figures 1d and 1e) and the highest number of casualty and displacements (Figure 1b) are identified, namely Region A (Selangor and Kuala Lumpur) and Region B (Pahang). Detailed analyses of the historical records over the two regions are provided in Text S1 in Supporting Information S1.

## 2.2. Tracking of the Flood-Causing MCSs

As the largest form of deep convective storms, MCSs have a wide distribution around the globe and bring heavy precipitation over many regions (e.g., Houze, 2015; Houze et al., 2019; Liu et al., 2021; Wang, et al., 2019). Located within the tropics, maritime continent is also a hot zone of MCSs, and more than half of its rainfall is caused by MCSs (Yuan & Houze, 2010).

To track MCSs at the global scale, especially for the regions without dense radar observational network, Feng et al. (2021) developed an algorithm using the inputs of satellite-observed infrared brightness temperature and quantitative precipitation estimate product. However, as suggested by the developers, the most long-lived MCSs are commonly found over the maritime continent, making the truncation of MCS lifecycle difficult as some systems show weak signal of dissipation because their spatial coverage is still well maintained above the size threshold due to the persistent barotropic forcing from the warm ocean. As a result, we further modified the tracking algorithm over the study region of the maritime continent, in order to segregate the MCS continuum when long-lived systems present but the corresponding precipitation declines notably. More specifically, the thresholds of area and mean rain rate of the precipitation feature associated with an MCS that are used to define the endpoint of tracking, have been tuned to the highest values tested in Wang et al. (2021).

## 2.3. Extraction of Synoptic Features

The Borneo Vortex (BV), notorious for the production of extreme winter precipitation over SEA, is a shallow, quasi-stationary, cyclonic circulation during the East Asian winter monsoon season from November to March with peak activity in December and January (Koseki et al., 2014; Ooi et al., 2011). It is typically located near the Borneo Island, and is commonly spun up by the cold surge brought by the equatorward propagation of cold air outbreaks that originates from the Siberian High (Chang et al., 2005; Chen et al., 1986; Johnson & Houze, 1987; Lau & Chang, 1987). The quasi-stationary nature of BV limits its area of influence mainly to Borneo Island, causing 60%–70% of local extreme winter precipitation (Liang et al., 2021). However, the anomalous equatorward and westward propagation of BV can also bring torrential rainfall over Indonesia and Peninsular Malaysia respectively (Liang et al., 2023). During the 16–18 December 2021 event, it has been confirmed that the flood-causing TD developed from the BV that

formed on 13 December 2021 over the northwest of Borneo (Liang et al., 2023). To examine the severity, propagation, and lifecycle of the tropical depression, the mean sea level pressure (MSLP) obtained from ERA5 hourly data on single levels is analyzed in this study. The TD acts like the heat engine that drives the convective updraft by releasing the convective available potential energy (CAPE; the maximum CAPE recorded on the peninsula was  $3610 \text{ J kg}^{-1}$  on 14 December 05:00). Meanwhile, abundant moisture transport is needed to “fuel the engine” and enhance precipitation.

To examine the intensity, spatial extent, and evolution of moisture supply that fueled the December 2021 event, the variable of integrated water vapor transport (IVT) commonly used for the identification of ARs (Ralph et al., 2018) is adopted in this study. The calculation is based on the inputs of ERA5 hourly data on pressure levels with the following equation:

$$\text{IVT} = \left[ \left( \frac{1}{g} \int_{1000\text{hpa}}^{300\text{hpa}} uqdp \right)^2 + \left( \frac{1}{g} \int_{1000\text{hpa}}^{300\text{hpa}} vqdp \right)^2 \right]^{1/2} \quad (1)$$

where  $g$  is gravitational acceleration,  $u$  and  $v$  are zonal and meridional winds respectively,  $q$  is specific humidity, and  $p$  is pressure.

### 3. Results

#### 3.1. The Spatiotemporal Characteristics of Flood-Causing MCSs

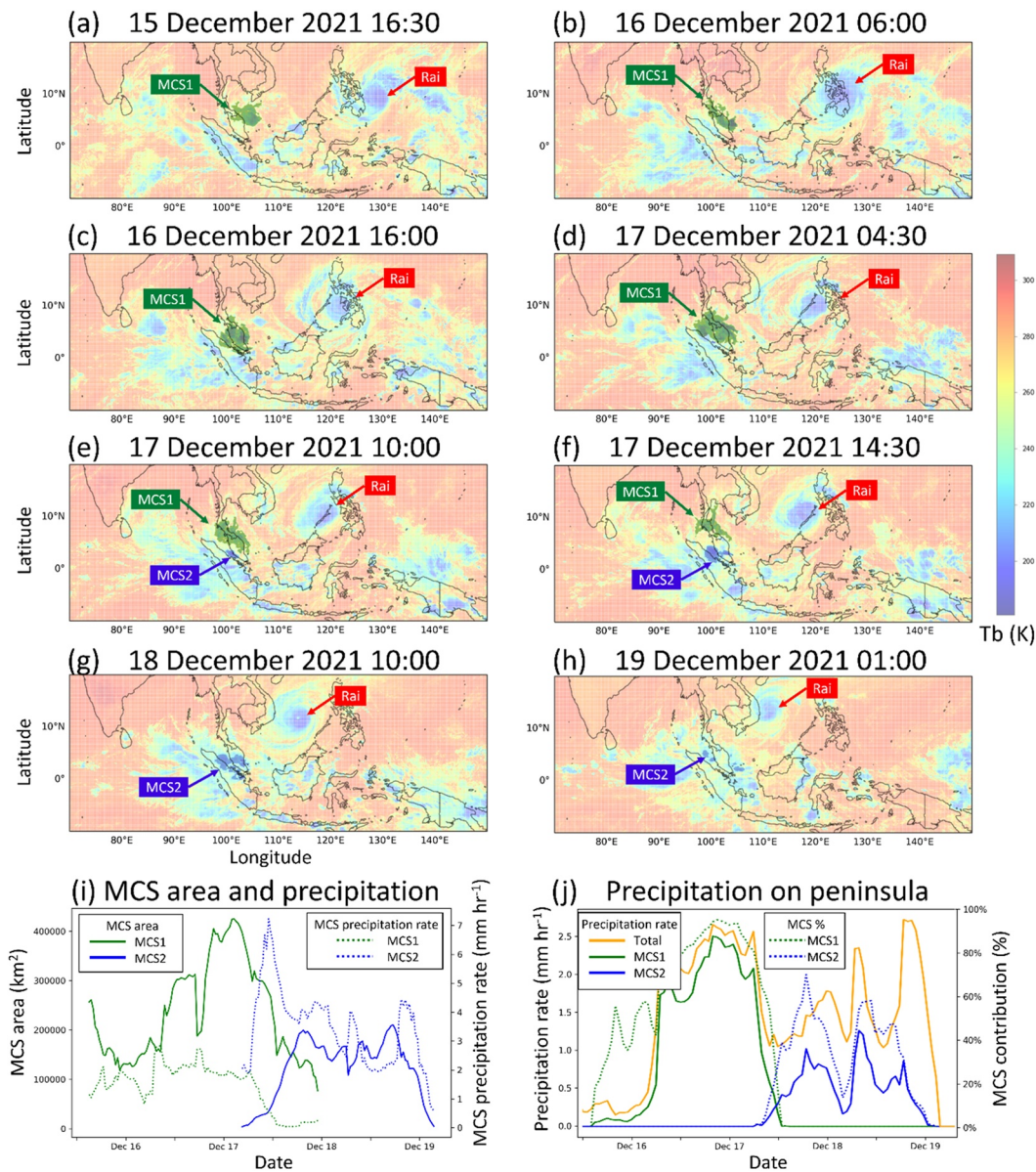
The key snapshots of MCS tracking result are shown in Figures 2a–2h. During the study period, the study domain of Peninsular Malaysia was dominated by two MCSs, which were labeled as MCS1 (green patch) and MCS2 (blue patch). The Super Typhoon Rai was also labeled, however it was more than 2,000 km east to the two systems, therefore MCS1 and MCS2 were originally considered independent to the typhoon system. The evolution of MCSs' precipitation features and their contribution to the flooding are shown in Figures 2i and 2j. More detailed analyses are available in Text S2 in Supporting Information S1.

Regarding the MCS precipitation features, MCS1 had a longer lifetime (57 vs. 47.5 hr), larger spatial coverage ( $234,000 \text{ km}^2$  vs.  $122,000 \text{ km}^2$  in average during their respective lifetime), and relatively weaker feature precipitation rate ( $1.42 \text{ mm hr}^{-1}$  vs.  $3.42 \text{ mm hr}^{-1}$ ; as defined in Text S2 in Supporting Information S1) compared to MCS2, however it made much greater contribution to the peninsular precipitation (77% vs. 32% during their respective lifecycles and 42% vs. 17% during the entire 3-day event). Such substantial contrast in the contribution of the two systems to the peninsular precipitation can be attributed to the fact that nearly 83% of the precipitation generated by MCS2 was dumped into the ocean. Therefore, the long-lasting land precipitation brought by MCS1 was the main contributor to the 2021 Peninsular Malaysia flood, and the synoptic features that govern the production of such system will be examined in the following section.

#### 3.2. The Evolution of Synoptic Drivers

As stated in Section 2.3, the westward propagating TD that originates from BV is the main synoptic driver for flooding over the Malay Peninsula, which serves as the heat engine of the drastic convection. However, a sufficient supply of water vapor which acts as the fuel injection to the engine is also indispensable in the production of torrential precipitation. Figure 3a shows the 3-day average MSLP and IVT over the broad maritime continent. Although the Super Typhoon Rai (enclosed by the 1,006 hPa isobar, with center at  $128^\circ\text{E}$ ) was the dominant weather system over the study domain, there was another relatively weaker low-pressure center (enclosed by the 1009 hPa) that hovers on the east coast of Malay Peninsula at  $106^\circ\text{E}$ , which was the flood-causing TD. Meanwhile, the peninsula was directly under the influence of a weak high-pressure center, which, together with the adjacent TD, formed a high-low pressure couplet. Such configuration enhanced the northerly flow over the east coast of the peninsular and promoted the occurrence of severe MCS.

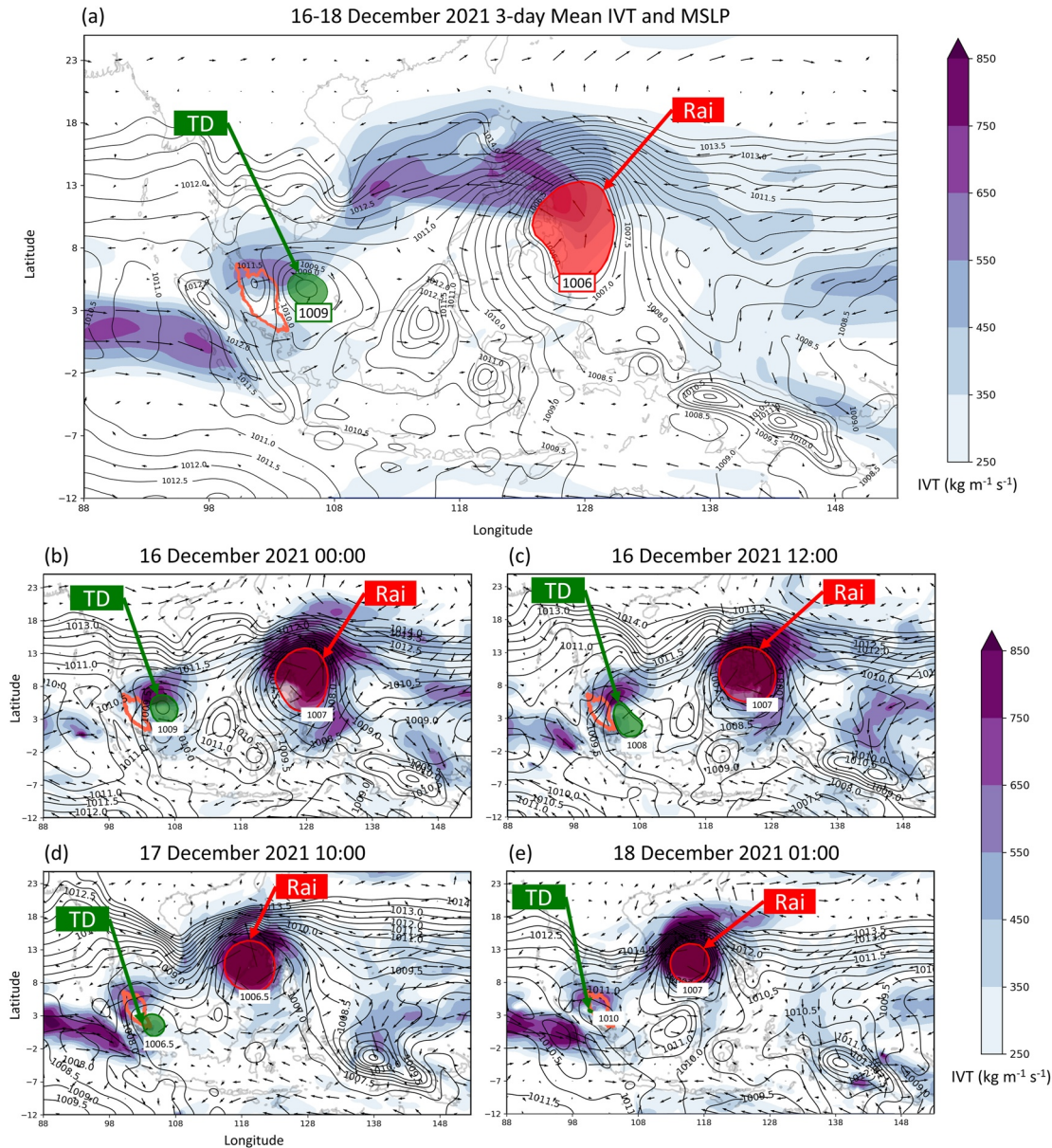
Despite the apparent separation between the TD couplet and Rai with a significant distance of over 2,000 km, it was evident that there existed a continuous moisture corridor that linked the two systems, whose IVT intensity exceeded  $250 \text{ kg m}^{-1} \text{ s}^{-1}$ . This long-lasting (3-day) water vapor transport originated from the northwest edge of Rai, where an excessive amount of water vapor ( $>600 \text{ kg m}^{-1} \text{ s}^{-1}$ ) was spun off from the severe cyclonic



**Figure 2.** (a–h) The MCS tracking results during the flood event at different key time steps, where the Super Typhoon Rai, MCS1, and MCS2 are labeled. (i) The time series of area of MCS1 (green solid line) and MCS2 (blue solid line), and their respective precipitation rate under the cloud shield (feature precipitation rate; dash lines). (j) The time series of hourly precipitation rate averaged over the entire Peninsular Malaysia (peninsular precipitation rate) from total (yellow solid line), MCS1 (green solid line), and MCS2 (blue solid line), as well as their fractional contribution to total precipitation (dash lines).

rotation, and was further propelled toward the peninsula by the long-range northeasterly wind. Even though the strength of IVT degraded southwestward toward the peninsula, it was still a considerable supplement (magnitude of  $300\text{--}400\text{ kg m}^{-1}\text{ s}^{-1}$ ) to the local moisture source ( $500\text{--}700\text{ kg m}^{-1}\text{ s}^{-1}$ ) over the northern peninsula that was collocated with the inlet region of the high-low pressure couplet. During the 3-day flooding period, the accumulated water vapor conveyed to the peninsula via the moisture channel, were it uniformly distributed, equated to an Integrated Water Vapor (IWV) of 57 mm (spatial average over the peninsula), while the outflow from the peninsula was 36 mm. Simultaneously, the mean IWV over the peninsula, regardless of the origin, was 62 mm. This finding unveils that the moisture conveyance by the water vapor corridor accounted for approximately 34% of the overall IWV over the peninsula, thus underscoring its significant contribution.

Such engine-fuel configuration (i.e., TD couplet combined with the strong long-distance transport of water vapor from Rai) composed a very favorable environment for the production of long-lasting, heavy-precipitating

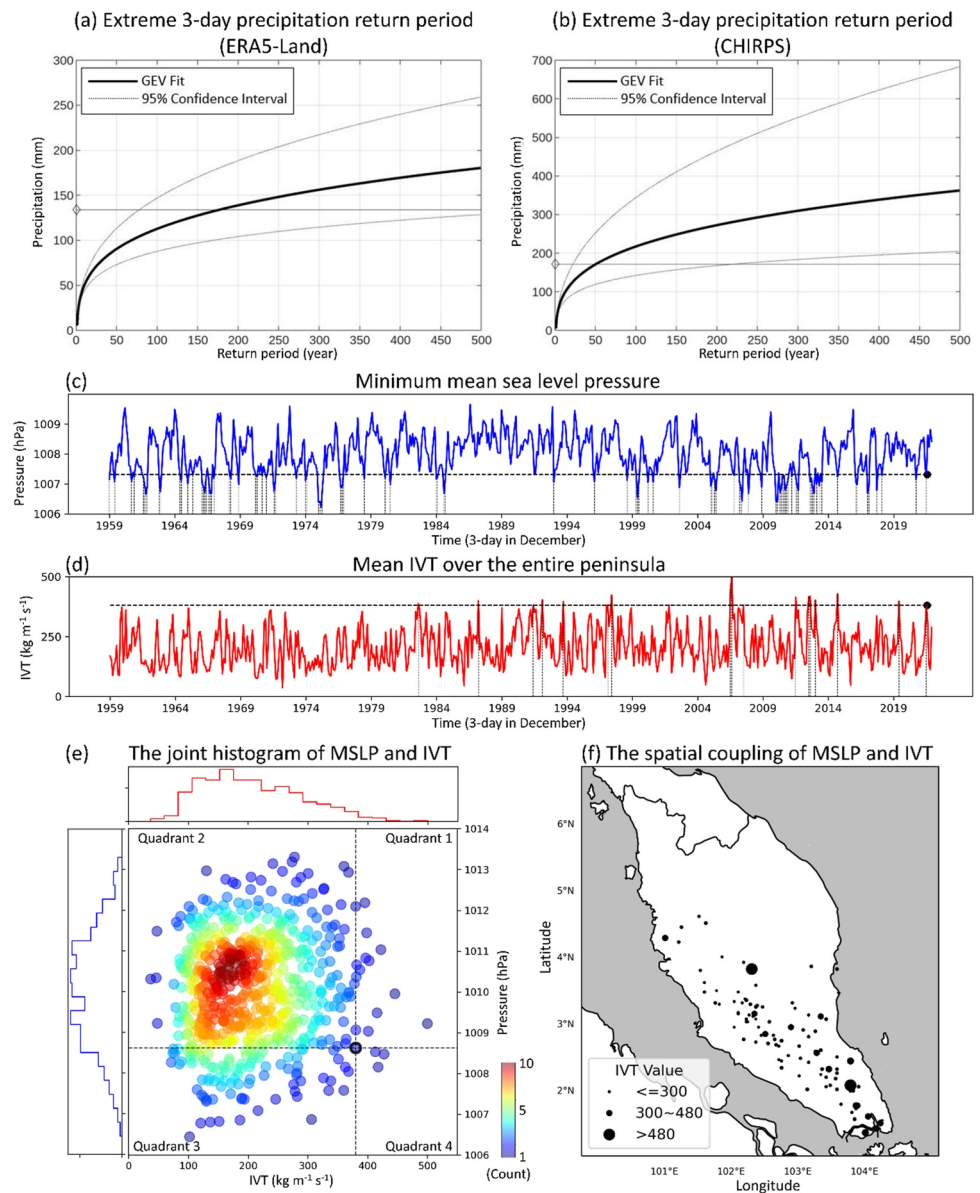


**Figure 3.** (a) The 3-day average of MSLP (contour lines), IVT (filled contours), and wind at 750 hPa (vectors) during the 16–18 December 2021 Peninsular Malaysia flood. The critical time steps in the evolution of synoptic features are shown for (a) 16 December 00:00, (b) 16 December 12:00, (c) 17 December 10:00, and (d) 18 December 01:00. The boundary of Peninsular Malaysia is highlighted in red.

thunderstorms, which was MCS1 as identified through storm tracking. The stepwise breakdown of the evolution of key synoptic features is illustrated in Figures 3b–3e and discussed in Text S3 in Supporting Information S1. It is noteworthy that the moisture channel was established as of 12 December at 12:00 also because of the Super Typhoon Rai (which formed on 11 December). The initial time steps are illustrated in Figure S3 in Supporting Information S1. Nevertheless, the tropical depression had not yet developed, and the moisture content over the peninsula was very low during that time.

### 3.3. Return Period of the Extreme Precipitation

Based on the statistical distribution for extreme events using the generalized extreme value (GEV) distribution (Jenkinson, 1955) using maximum likelihood estimates, the return periods of the December 3-day total precipitation over the entire Peninsular Malaysia were calculated using the 72-year (1950–2021) ERA5-Land precipitation



**Figure 4.** The return period of extreme 3-day precipitation in December over Peninsular Malaysia estimated based on generalized extreme value (GEV) distribution with the input of (a) ERA5-Land precipitation and (b) CHIRPS precipitation. (c) The time series of 3-day minimum mean sea level pressure (MSLP) in December over the peninsula, where the dotted lines indicate the events whose MSLP is lower than the 2021 event. (d) The time series of 3-day mean integrated water vapor transport (IVT) averaged over the peninsula, where the dotted lines indicate the events whose IVT is higher than the 2021 event. (e) The joint histogram of MSLP and IVT. (f) The spatial distribution of the locations of tropical depression (defined as the minimum MSLP over the peninsula) and the corresponding IVT.

(Figure 4a) and 41-year (1981–2021) CHIRPS data (Figure 4b) respectively. According to ERA5-Land data, the return period of the event with 3-day accumulated precipitation exceeding 134.0 mm (averaged over the entire peninsula) in December was 178 years (78 and 605 years for the 95% confidence intervals). Similarly, the return period estimated with the input of CHIRPS data for precipitation more than 171.5 mm was 51 years (with confidence intervals ranging from 22 to 223). Given the fact that the span of CHIRPS data is about half of that of ERA5-Land, its goodness of fitting may not be as optimal as its counterpart (Figure S2 in Supporting Information S1). It is worth noting that CHIRPS might exhibit lower reliability than ERA5 reanalysis or observational data, since it was developed based on a pentad and is not designed to be used on daily precipitation. Therefore, we are more confident toward the result of ERA5-Land.

In addition to the return period inferred solely based on precipitation records, Chang et al. (2003) suggests the joint probability of key meteorological drivers to the extreme events can also provide a robust estimation of their return period. As discussed in Section 3.2, the presence of strong TD and the excessive IVT injection respectively acted as the engine and fuel that propelled the catastrophic rainfall event. To determine the frequency of extreme occurrences on 16–18 December 2021, the time series of the two drivers are analyzed in Figures 4c and 4d.

From the historical 3-day minimum MSLP sequence in December, there were 95 out of 630 (10 intervals  $\times$  63 years) cases with minimum MSLP over the peninsula lower than the 16–18 December 2021 event (Figure 4c), which converted to the occurrence frequency of 15.0% (96/630) with a return period of 7 years. Similarly, there were 16 cases with IVT higher than the event, resulting in the occurrence frequency of 2.7% (17/630) and the return period of this anomaly was approximately 37 years. Even though the independent probabilities of the two key drivers conducive to the torrential rainfall over the peninsula were not extremely low, the probability of their concurrent occurrence was much lower. As shown in Figure 4e, the joint probability for the event of study was 0.6% (4/630; the occurrences within quadrant 4 divided by the occurrences in all 4 quadrants orthogonally partitioned by the IVT and MSLP thresholds), and the corresponding return period was 158 years. The proxy-based estimate aligned well with one solely based on precipitation records, revealing the 2021 Peninsular Malaysia flood was indeed an event that happens on average once every 150 years, assuming a stationary climate.

It should be emphasized that all the calculations were conducted over the entire peninsula. However as highlighted in Sections 2.1 and 3.2, the location of the precipitation was also critical since only the upwind side of Titiwangsa Mountain and its southwest foothill have the potential to form catastrophic flood when exposed to torrential rainfall. Figure 4f illustrates the locations of all 96 low TD events with their respective IVT labeled. The 3 events with IVT values higher than the 2021 event all occurred over the southeast tip of the peninsula, where intense precipitation discharged rapidly into the ocean. Therefore, since the region that is vulnerable to flood only covers about 30% of the entire peninsula (Figure 1a), the actual return period of the 2021 incident is expected to be even longer.

#### 4. Conclusions and Discussion

Having an accurate understanding of the flood-causing storms and their specific synoptic configuration is essential for precise flood outlook and forecasting. By using a refined storm tracking algorithm, this study identified that the catastrophic 2021 Peninsular Malaysia flood was caused by two consecutive MCSs that produced record-breaking precipitation over a period of 3 days. Through the examination of their spatiotemporal evolution, this study revealed that the first MCS made much greater contribution to the peninsular precipitation than the second one. Specifically, the first MCS contributed 77% to the total precipitation over the peninsula during its lifespan and 42% throughout the event, while the second MCS only contributed 32% and 17%, respectively. These findings provide valuable validation data set for the follow-up modeling studies of this event.

Moreover, based on the analysis of synoptic environment, two key drivers conducive to the production of the two flood-causing MCSs are identified, namely the slow-moving TD, which acted as the engine that drove the convective updraft by releasing the CAPE, and the long-range, long-lasting, easterly strong water vapor corridor that fueled excessive moisture from the Super Typhoon Rai to the TD. The return period estimated solely based on statistical modeling of precipitation records aligned well with the joint probability of key synoptic drivers with only a 20-year difference (178 vs. 158 years). Nonetheless, both of these estimations reveal the 2021 Peninsular Malaysia flood was more severe than a “once-in-a-century” event reported by mainstream media.

Last and most importantly, such water vapor corridor with magnitude similar to the 16–18 December 2021 event is not uncommon over SEA as evidenced by Figures S4 and S5 in Supporting Information S1, whose occurrence did not necessarily depend on the presence of a typhoon system. In those anomalous moisture channel events, the absence of convective triggers like TD, prevented the formation of severe precipitation, therefore the intense moisture merely passed through the region. This, however, does not imply that the risk of flooding events with comparable or even greater magnitude than the 2021 Peninsular Malaysia flood remains constant. Based on historical data, there were just 7 moisture channel events stronger than the study event observed from 1950 to 2000 (Figure S4 in Supporting Information S1). However, within the recent 20 years, this count has risen to 9 (Figure S5 in Supporting Information S1), signifying an escalating likelihood of occurrences of such events after 2000. Therefore, it becomes critical to prioritize the vigilance and monitoring of such anomalous phenomena in the forecasting and risk assessment of winter flooding in SEA.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

All Python codes used for data processing and visualization, as well as the raw data are deposited in a Zenodo repository in Wang (2023).

## Acknowledgments

This research is supported by the National Institute of Education, Singapore, under its Academic Research Fund (RI 5/22 WJY), Academic Research Fund Tier 2 (MOE-T2EP402A20-0001 to E. P.) and (MOE-MOET2EP10121-0008 to X. W.). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the National Institute of Education, Singapore. This work comprises Earth Observatory of Singapore contribution No. 559.

## References

- BERNAMA. (2022). Floods claim 54 lives so far, two still unaccounted for - Bukit Aman. *BERNAMA*. Retrieved from [https://www.bernama.com/en/general/news\\_disaster.php?id=2040627](https://www.bernama.com/en/general/news_disaster.php?id=2040627)
- Chang, C.-P., Harr, P. A., & Chen, H.-J. (2005). Synoptic disturbances over the equatorial South China Sea and western Maritime Continent during boreal winter. *Monthly Weather Review*, *133*(3), 489–503. <https://doi.org/10.1175/MWR-2868.1>
- Chang, C.-P., Liu, C.-H., & Kuo, H.-C. (2003). Typhoon Vamei: An equatorial tropical cyclone formation. *Geophysical Research Letters*, *30*, 1150. <https://doi.org/10.1029/2002GL016365>
- Chen, G. T. J., Gerish, T. E., & Chang, C.-P. (1986). Structure variations of the synoptic-scale cyclonic disturbances near Borneo during WMONEX period. *Paper Meteorological Research*, *9*, 117–135. <https://doi.org/10.1175/MWR-2868.1>
- Feng, Z., Leung, L. R., Liu, N., Wang, J., Houze, R. A., Li, J., et al. (2021). A global high-resolution mesoscale convective system database using satellite-derived cloud tops, surface precipitation, and tracking. *Journal of Geophysical Research: Atmospheres*, *126*(8), e2020JD034202. <https://doi.org/10.1029/2020JD034202>
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., et al. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*(1), 150066. <https://doi.org/10.15780/G2RP4Q>
- Hassan, H. (2021). Peninsular Malaysia hit by “1-in-100-year” rainfall, govt says amid severe flooding. *Meteorological Drivers of the Extreme Precipitation Event and Devastating Floods of Early-February 2021 in Semarang, Central Java, Indonesia*, *Atmosphere*, *13*(7), 1092. <https://doi.org/10.3390/atmos13071092>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Houze, R. A., Rasmussen, K. L., Zuluaga, M. D., & Brodzik, S. R. (2015). The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the tropical rainfall measuring mission satellite. *Reviews of Geophysics*, *53*(3), 994–1021. <https://doi.org/10.1002/2015RG000488>
- Houze, R. A., Wang, J., Fan, J., Brodzik, S., & Feng, Z. (2019). Extreme convective storms over high-latitude continental areas where maximum warming is occurring. *Geophysical Research Letters*, *46*(7), 4059–4065. <https://doi.org/10.1029/2019GL082414>
- Jenkinson, A. F. (1955). The frequency distribution of the annual maximum (or minimum) values of meteorological elements. *Quarterly Journal of the Royal Meteorological Society*, *81*(348), 158–171. <https://doi.org/10.1002/qj.49708134804>
- Johnson, R. H., & Houze, R. A., Jr. (1987). Precipitating cloud systems of the Asian monsoon. In C.-P. Chang & T. N. Krishnamurti (Eds.), *Monsoon meteorology* (pp. 298–353). Oxford University Press.
- Koseki, S., Koh, T.-Y., & Teo, C.-K. (2014). Borneo vortex and mesoscale convective rainfall. *Atmospheric Chemistry and Physics*, *14*(9), 4539–4562. <https://doi.org/10.5194/acp-14-4539-2014>
- Lau, K.-M., & Chang, C.-P. (1987). Planetary scale aspects of winter monsoon and Teleconnections. In C.-P. Chang & T. N. Krishnamurti (Eds.), *Monsoon meteorology* (pp. 161–202). Oxford University Press.
- Liang, J., Catto, J. L., Hawcroft, M., Hodges, K. I., Tan, M. L., & Haywood, J. M. (2021). Climatology of Borneo vortices in the HadGEM3-GC31 general circulation model. *Journal of Climate*, *34*(9), 3401–3419. <https://doi.org/10.1175/JCLI-D-20-0604.1>
- Liang, J., Catto, J. L., Hawcroft, M. K., Tan, M. L., Hodges, K. I., & Haywood, J. M. (2023). Borneo Vortices in a warmer climate. *npj Climate and Atmospheric Science*, *6*(1), 2. <https://doi.org/10.1038/s41612-023-00326-1>
- Liu, N., Leung, L. R., & Feng, Z. (2021). Global mesoscale convective system latent heating characteristics from GPM retrievals and an MCS tracking dataset. *Journal of Climate*, *34*(21), 8599–8613. <https://doi.org/10.1175/JCLI-D-20-0997.1>
- Malay Mail. (2021). National Disaster Control Centre calls for states with risk of heavy rain to activate disaster management committees. *Malay Mail*. Retrieved from <https://www.malaymail.com/news/malaysia/2021/12/16/national-disaster-control-centre-calls-for-states-with-risk-of-heavy-rain-t/2029011>
- National Disaster Command Centre (NDCC). (2021). Retrieved from <https://web.archive.org/web/20211220151030/>
- Ooi, S. H., Samah, A. A., & Braesicke, P. (2011). A case study of the Borneo Vortex genesis and its interactions with the global circulation. *Journal of Geophysical Research*, *116*(D21), D21116. <https://doi.org/10.1029/2011JD015991>
- Ralph, F. M., Dettinger, M., Cairns, M. M., Galarneau, T. J., & Eylander, J. (2018). Defining “atmospheric river”: How the glossary of meteorology helped resolve a debate. *Bulletin of the American Meteorological Society*, *99*(4), 837–839. <https://doi.org/10.1175/BAMS-D-17-0157.1>
- Stull, R. (2017). *Practical meteorology: An algebra-based survey of atmospheric science*. University of British Columbia. 978-0-88865-283-6.
- Wang, J. (2023). Data for article “is the 2021 Peninsular Malaysia flood truly A ‘once-in-a-century’ event?”: Version1 (v1.0.0). [Dataset]. Zenodo. <https://doi.org/10.5281/zenodo.7795712>
- Wang, J., Fan, J., Feng, Z., Zhang, K., Roesler, E., Hillman, B., et al. (2021). Impact of a new cloud microphysics parameterization on the simulations of mesoscale convective systems in E3SM. *Journal of Advances in Modeling Earth Systems*, *13*(11), e2021MS002628. <https://doi.org/10.1029/2021MS002628>
- Wang, J., Houze, R. A., Jr., Fan, J., Brodzik, S. R., Feng, Z., & Hardin, J. C. (2019). The detection of mesoscale convective systems by the GPM Ku-band spaceborne radar. *Journal of the Meteorological Society of Japan*, *97*(6), 1059–1073. Special Edition on Global Precipitation Measurement (GPM): 5th Anniversary. <https://doi.org/10.2151/jmsj.2019-058>
- Yuan, X., & Houze, J. (2010). Global variability of mesoscale convective system anvil structure from A-Train satellite data. *Journal of Climate*, *23*(21), 5864–5888. <https://doi.org/10.1175/2010JCLI3671.1>

## References From the Supporting Information

- Bari, A., Alam, L., Alam, M. M., Rahman, L. F., & Pereira, J. J. (2021). Estimation of losses and damages caused by flash floods in the commercial area of Kajang, Selangor, Malaysia. *Arabian Journal of Geosciences*, *14*(3), 195. (online). <https://doi.org/10.1007/s12517-021-06503-x>